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A Method for Synthesis and Selection of Propulsion Plants for Submarines

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By
James F. Blose and Joseph F. McCartney

JAMES F. BLOSE

JOSEPH F. McCARTNEY

Approved by:

H. R. BOROSON
Special Projects Division

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ABSTRACT

NEW CONCEPTS FOR SUBMARINE PROPULSION PLANTS ARE CONTINUOUSLY BEING PRESENTED TO THE NAVY FOR REVIEW AND POSSIBLE APPLICATION. AN ANALYTICAL METHOD IS NOW BEING USED TO DETERMINE THE EFFECT OF POWER PLANT WEIGHT AND THERMAL EFFICIENCY ON THE CRUISING RADIUS, SPEED, AND VESSEL DISPLACEMENT. A MATHEMATICAL MODEL REPRESENTING THE PROPULSION PLANT AND VESSEL HULL WAS PREPARED AND, BY MEANS OF A DIGITAL COMPUTER, THE EFFECTS OF VARYING SEVERAL DESIGN PARAMETERS WERE STUDIED. BY COMPARING THE PREDICTED PERFORMANCE OF SEVERAL TYPES OF POWER PLANTS WITH THE RESULTS OF THE COMPUTER STUDY IT IS POSSIBLE TO SELECT THOSE WHICH JUSTIFY FURTHER DEVELOPMENT FOR NAVY USE.

ADMINISTRATIVE INFORMATION

This report was prepared as part of MEL Assignment 75 521 which was authorized by BUSHIPS letter SF013 01 03 Ser 430-068 of 20 December 1962. The work was performed under Sub-project SF013 01 03, Advanced FBM Studies, Task 0218, Propulsion System Analysis. To expedite progress of these analyses, two study contracts were awarded to the Westinghouse Electric Company, Contract Numbers N600(61533)61294 and N600(61533)61394, to supplement studies in progress at MEL. These cover Propulsion Systems and Electrical Ancillaries to Propulsion Systems, respectively. Westinghouse sub-contractors include Hydronautics, Incorporated, and Stein Seal Company, in addition to their own Marine Systems Engineering Department, Research and Development Center, Development Engineering Department and Advanced Systems Engineering Department.

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A METHOD FOR SYNTHESIS AND SELECTION OF PROPULSION PLANTS FOR SUBMARINES

INTRODUCTION

UNTIL DEVELOPMENT OF THE NUCLEAR POWERED SUBMARINE, ALL AMERICAN SUBMARINES USED AN INTERNAL COMBUSTION ENGINE WHEN SURFACED AND ELECTRIC MOTORS POWERED BY BATTERIES WHEN SUBMERGED. WHILE THE ADOPTION OF THE SNORKEL AFTER WORLD WAR II GREATLY EXTENDED THE NEAR-SURFACE ENDURANCE, IT DID NOT EXTEND THE FULLY SUBMERGED OPERATION.

POWER PLANTS CAPABLE OF OPERATION FOR PROTRACTED PERIODS WHEN FULLY SUBMERGED HAVE BEEN SOUGHT FROM THE CONCEPTION OF THE FIRST SUBMARINE. PROMISING RESULTS WERE OBTAINED IN GERMANY AS EARLY AS 1907 WITH A CLOSED-CYCLE, INTERNAL-COMBUSTION ENGINE, OPERATING ON GASOLINE AND BOTTLED OXYGEN.(1) HOWEVER, THE STORAGE OF LARGE VOLUMES OF PURE OXYGEN UNDER A PRESSURE OF 200 ATMOSPHERES WAS THEN CONSIDERED TO BE TOO HAZARDOUS, AND THE PROJECT WAS DROPPED. SUCH A SYSTEM WAS UNDER ACTIVE DISCUSSION IN THE UNITED STATES BEFORE WORLD WAR I.(2) ACCORDING TO SCIENTIFIC AMERICAN,(3) CONGRESS AUTHORIZED CONVERSION OF AN E-TYPE SUBMARINE TO OPERATE ON THE NEFF CLOSED-CYCLE SYSTEM IN A 1917 APPROPRIATION BILL; HOWEVER, THERE IS NO RECORD THAT IT WAS EVER COMPLETED.

INTEREST IN CLOSED-CYCLE POWER PLANTS LAPSED IN THIS COUNTRY, ALTHOUGH IT CONTINUED ACTIVE IN OTHERS, UNTIL WORLD WAR II. ALARM OVER REPORTED ENEMY SUCCESSES WITH SNORKEL AND CLOSED-CYCLE SYSTEMS SPARKED A REVIVAL OF INTEREST WHICH LED TO NAVY SPONSORSHIP OF RESEARCH

and development on closed-cycle diesel and gas turbine engines,[4] a Walter-cycle, hydrogen peroxide-diesel-fuel-burning, steam-gas turbine plant,[5] a steam plant,[4] and finally the nuclear power plant. When this proved satisfactory, development of competitive systems was discontinued.

Several countries have built submarines powered by closed-cycle power plants, including the United States. The midget submarines used by the Japanese in the December 7, 1941, attack on Pearl Harbor, as well as midget Italian submarines used in World War II, were powered by closed cycle internal combustion engines.

The American submarine, X-1, commissioned in 1954 and described in references (4) and (6), was powered when submerged by a closed-cycle diesel engine which operated on diesel fuel and oxygen from decomposed hydrogen peroxide. The peroxide tankage and all closed cycle capability were removed from this boat several years ago, following a fire. The British installed Walter-cycle, hydrogen peroxide-diesel-fuel-burning, steam-gas turbine power plants in a new class of submarines in 1954.[7] These were used to supplement battery power when bursts of speed were required for short periods when under way submerged. They were not considered suitable for continuous use due to their relatively high fuel consumption.

The Marine Engineering Laboratory is reviewing previous applications of these systems and is studying current technology to determine those areas that might require further research and development if they are to find application in specific ships. Submarines designed for operation at greater depths will require thicker and heavier hulls.

As a result, machinery must be more compact, efficient, and lighter than that heretofore used. It should also be quieter, more reliable, and subject to a greater degree of automatic control.

Many types of propulsion systems are being studied. Some of these are not applicable for most missions. The nature and duration of the mission assigned to the ship, as yet unspecified, will be the dominant factor in selecting an optimum system. A schematic diagram of the propulsion system analysis is shown in Figure 1. It should be noted that these are not simple building blocks that may be indiscriminately combined. For example, the use of solid fuels would be incompatible with the use of a closed cycle diesel engine. The characteristics to be studied for each system are shown in Figure 2.

Fuels and Oxidants

Fuels and oxidants are being surveyed to determine which combination offers the best overall performance. Density of energy storage, ease of handling, toxicity, calorific value, and problems in disposing of combustion products will be compared. Some of those being studied are listed in Table 1. Calculations in this paper are based on the use of liquid oxygen as an oxidant. Other oxidants, capable of being stored at normal ambient temperatures and pressures, are also being studied. To minimize the problems in handling solid fuels, a metal fuel can be prepared in powdered form and blended with a liquid fuel to form a stabilized slurry which will have a calorific value intermediate between that of the solid and liquid fuel. Other high energy density fuels, including the metal hydrides, [8] have high calorific values and must be considered.

PROPULSION SYSTEM A

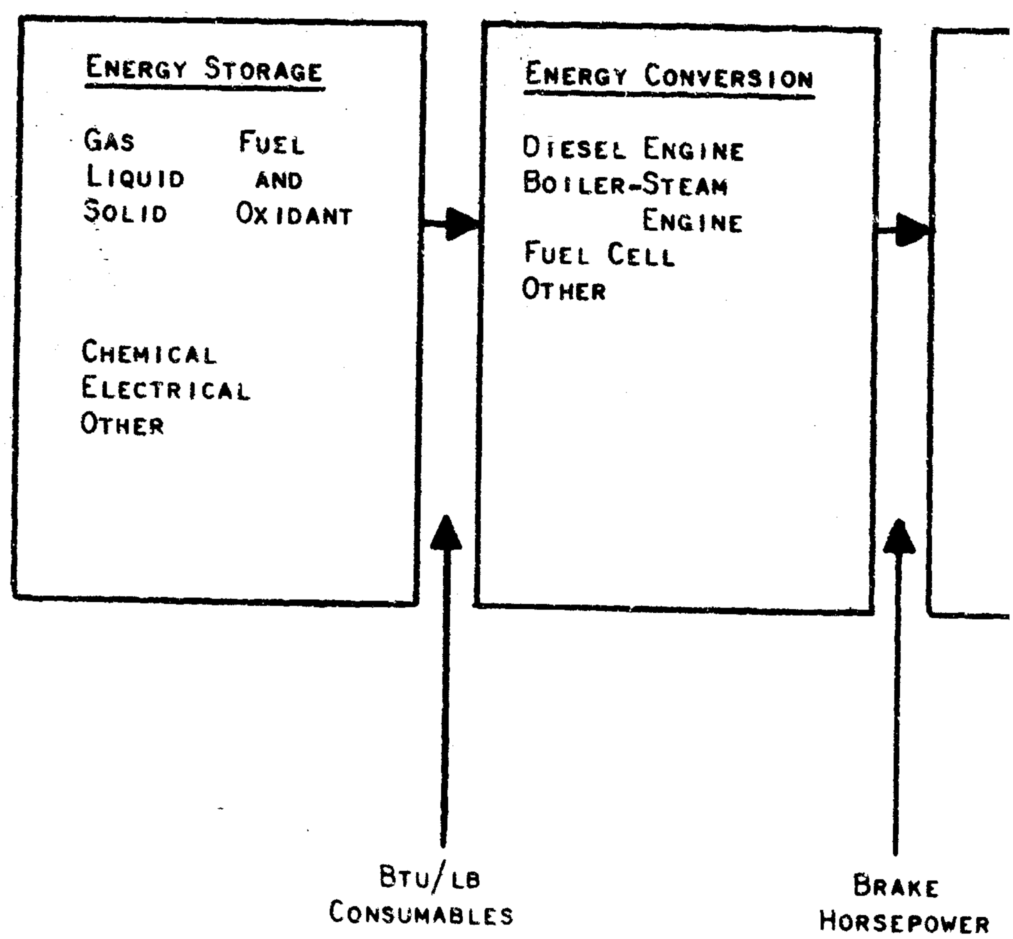
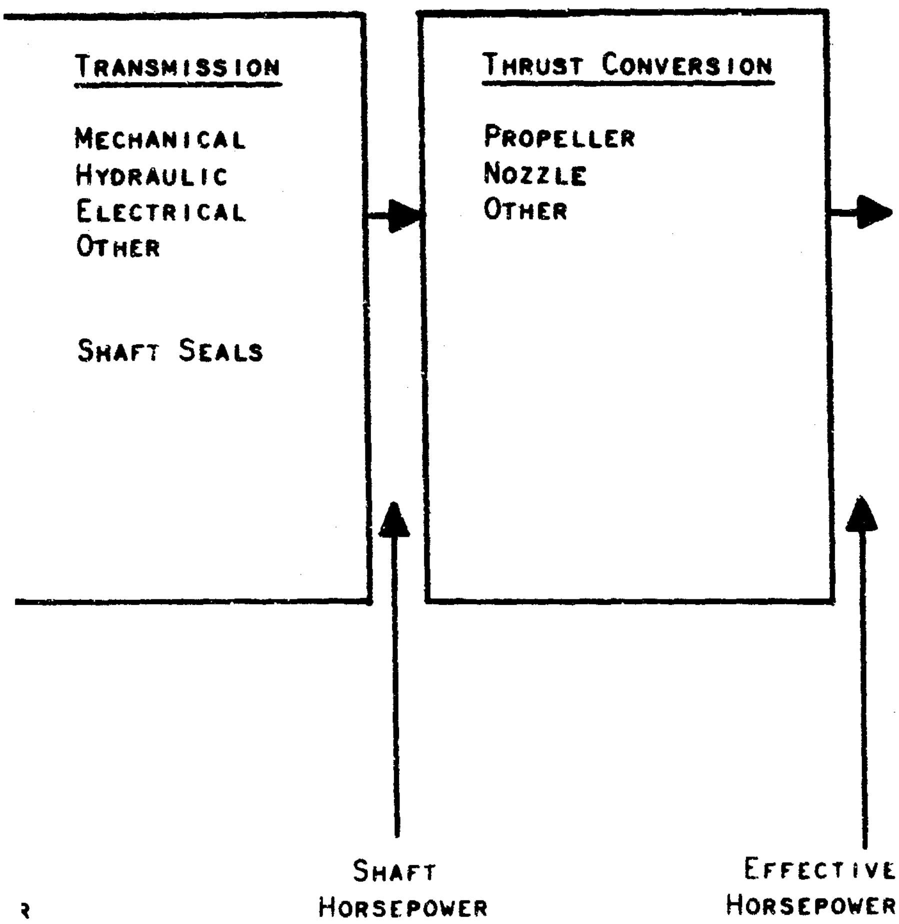


FIGURE 1

ANALYSIS


TRANSMISSION
MECHANICAL
HYDRAULIC
ELECTRICAL
OTHER
SHAFT SEALS
THRUST CONVERSION
PROPELLER
NOZZLE
OTHER
SHAFT HORSEPOWER
EFFECTIVE HORSEPOWER

Characteristics to be Studied for Each System

1. Weight and volume of machinery, including a configuration of each plant to a hull.
2. Efficiency of machinery and rate of consumption of fuel and oxidant at different cruising speeds.
3. Exhaust disposal.
4. Noise characteristics and resistance to shock.
5. Heat rejection.
6. Reliability and maintenance problems. Consequences of derangements. Predicted life of major components.
7. Logistic support problems. Fuel oxidant, spare parts, etc.
8. Development effort required and potential for growth.
9. Feasibility of installing major components external to the pressure hull.
10. Maneuverability and power demand response.
11. Cost of development, manufacture, and operation.

Figure 2

Table 1

Characteristics of Fuels and Oxidants

Fuel	Specific Gravity	Btu/lb Consumables[1]	Oxygen/Fuel Weight Rates	Mean Specific Gravity of Consumables[1]
Fuels				
Beryllium	1.85	10,300	1.76	1.324
Lithium	0.53	8,590	1.15	0.746
Boron	2.33	7,900	2.22	1.368
Aluminum	2.70	7,060	0.89	1.641
Hydrogen	0.071 at -423 F	5,780	7.94	0.424
Diesel Fuel Oil	0.84	4,370	3.43	1.054
Pentaborane	0.62	7,150	3.04	0.951
Aluminum Borohydride	0.54	6,300	2.67	0.875

Oxidant	Specific Gravity	Boiling Point F	Freezing Point F	Mean Specific Gravity of Consumables[3]
Oxidants				
Liquid Oxygen	1.14 at boiling point	-297	-361	1.054
Gaseous Oxygen[2]	0.237	-297	-361	0.283
Hydrogen Peroxide	1.463	306	29	1.20
Perchloryl Fluoride	1.43	116	-231	1.29

1 - Based on the use of liquid oxygen.
2 - At 3000 psi pressure.
3 - With diesel fuel oil.

Water-reacting fuels, such as lithium and sodium, appear attractive, since they do not require the ship to carry a supply of oxidant. Performance data[9] indicate that lithium is highly effective. Sodium which is cheaper and in more abundant supply was shown to have an appreciably higher rate of consumption.

The hydrocarbon fuels are the cheapest and most universally available. Hydrogen and methane, which have the highest heating values, are gases at normal ambient temperatures and may be better stored as cryogenic liquids. Other hydrocarbon fuels do not vary greatly in net heating value. Jet-engine and diesel-engine fuels are most attractive for use, since they are currently used in great quantities and offer few problems of distribution or storage.

Other Sources of Energy

Storage batteries, heat storage in molten salts, as proposed in reference (10), and electrical energy stored in superconducting solenoids[11] are considered potentially suitable for the low-energy submerged missions.

Energy Conversion

The following types of energy conversion are among those being considered:

a. Internal combustion (closed cycle diesel engine).

b. External combustion (with regeneration).

(1) Closed-cycle gas turbine.

(2) Steam engine or turbine.

(3) Stirling-cycle engine.

c. Fuel cells.

D. Magnetohydrodynamic generator.

E. Thermionic generator.

F. Thermoelectric generator.

The performance of heat engines is restricted by the limited endurance of structural materials at elevated temperatures. It is necessary to limit combustion chamber temperatures by diluting the reactants, usually with water or recycled exhaust gas. As new, high-strength, high-temperature materials are developed and applied, the efficiencies of all heat engines will improve. To attain high efficiencies, heat engines will require the use of the maximum amount of regeneration permitted by the space and weight allowance for the power plant. Fuel cells are not, in general, subject to this limitation, since they are not governed by the same thermodynamic laws as heat engines and can be efficiently operated at moderate temperatures. An economical method for disposal of noncondensable gases in combustion exhaust products has not yet been achieved.

Transmissions

The following types of power transmission are being evaluated:

A. Electrical generator and motor.

B. Hydraulic pump and motor.

C. Gear and friction drives.

D. Clutches and couplings.

E. Torque converters.

While the efficiency of the gear drive may not be bettered, a quieter or otherwise more desirable transmission may be obtained. The propeller-shaft seal and thrust bearing offer difficult design

PROBLEMS. THE PROPELLER-SHAFT THRUST BEARING AND ITS SUPPORTING STRUCTURE MUST CARRY BOTH THE PROPELLER THRUST AND THE HYDROSTATIC PRESSURE DUE TO DEPTH. ROTATING HULL PENETRATIONS CAN BE ELIMINATED BY THE USE OF SUBMERGED ELECTRIC OR HYDRAULIC MOTORS. THESE MOTORS DO NOT REQUIRE COMPLEX SHAFT SEALS AND, SINCE BOTH ENDS OF THE SHAFT ARE EXPOSED TO DEPTH PRESSURE, THE THRUST BEARING CARRIES ONLY THE PROPELLER THRUST. WATER-LUBRICATED SUBMERGED MOTORS ARE NOW UNDER DEVELOPMENT IN SEVERAL LABORATORIES, INCLUDING OUR OWN.

Power-to-Thrust Conversion

THE PERFORMANCE OF NOZZLES AND JET PUMPS IS BEING COMPARED WITH THAT OF SCREW PROPELLERS. THE USE OF MULTIPLE POWER PODS IN PLACE OF SOME OF THE CONTROL SURFACES IS A POSSIBILITY. MAGNETOHYDRODYNAMIC PROPULSION APPEARS ATTRACTIVE SINCE IT PRODUCES NO GEAR OR CAVITATION NOISE.

Synthesis of Applied Propulsion Plants

VARIATIONS IN PROPULSION PLANTS SIMILAR TO THOSE PREVIOUSLY DISCUSSED AND OTHERS WHICH REPRESENT TOTALLY NEW CONCEPTS ARE CONTINUALLY BEING PROPOSED AND MUST BE REVIEWED BY THE NAVY. EACH REVIEW MUST NOT ONLY VERIFY THE PREDICTED PERFORMANCE AND OTHER CHARACTERISTICS OF THE PROPOSED PLANTS BUT MUST ALSO EVALUATE THE POTENTIAL BENEFITS OF THE PROPOSED PLANTS TO PARTICULAR SHIPS AND MISSIONS. THE CONTINUING REVIEW OF PROPULSION PLANTS INVOLVES A CONSIDERABLE AMOUNT OF ENGINEERING EFFORT. TO EXPEDITE THIS PROCESS, A MATHEMATICAL MODEL, REPRESENTING THE PERFORMANCE OF THE PROPULSION PLANTS AND VESSELS, WAS PREPARED, AND BY MEANS OF A FORTRAN COMPUTER PROGRAM

SOAPS (Synthesis of Applied Propulsion Systems), the effects of varying several design parameters are studied.

The program may be briefly described as follows:

A. Referring to Figure 3, a value representing payload is inserted into the program.

B. A pressure hull capable of the submerged depth envelopes the payload providing neutral buoyancy for the payload and hull weights.

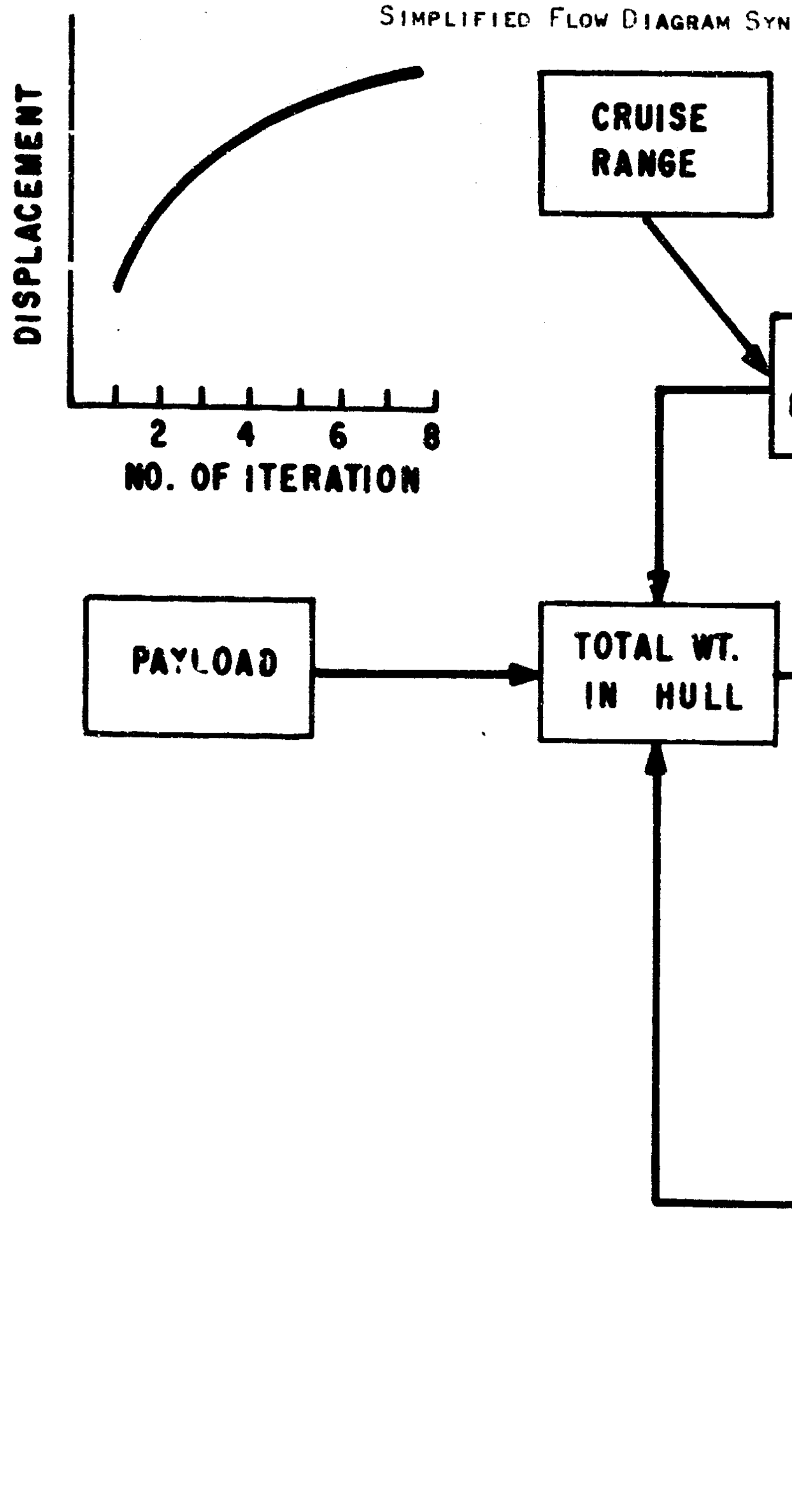
C. Propulsion-machinery requirements are computed, and the weight of the components is added to the basic payload and hull weight.

D. Fuel and oxidant quantities are computed from criteria representing missions energy requirements, and this weight is added to the payload, hull, and propulsion machinery weights.

E. The computer proceeds to iterate the combined weights tracing the loops with a provision to test the rate of change of the submerged displacement at each successive iteration. When the rate of change of submerged displacement settles down to a predetermined value, the program stops and the data of the final iteration is printed out. The growth of submerged displacement with each iteration is shown at the upper left-hand corner of Figure 3. This growth is due to the successive addition of consumables and propulsion machinery with each iteration.

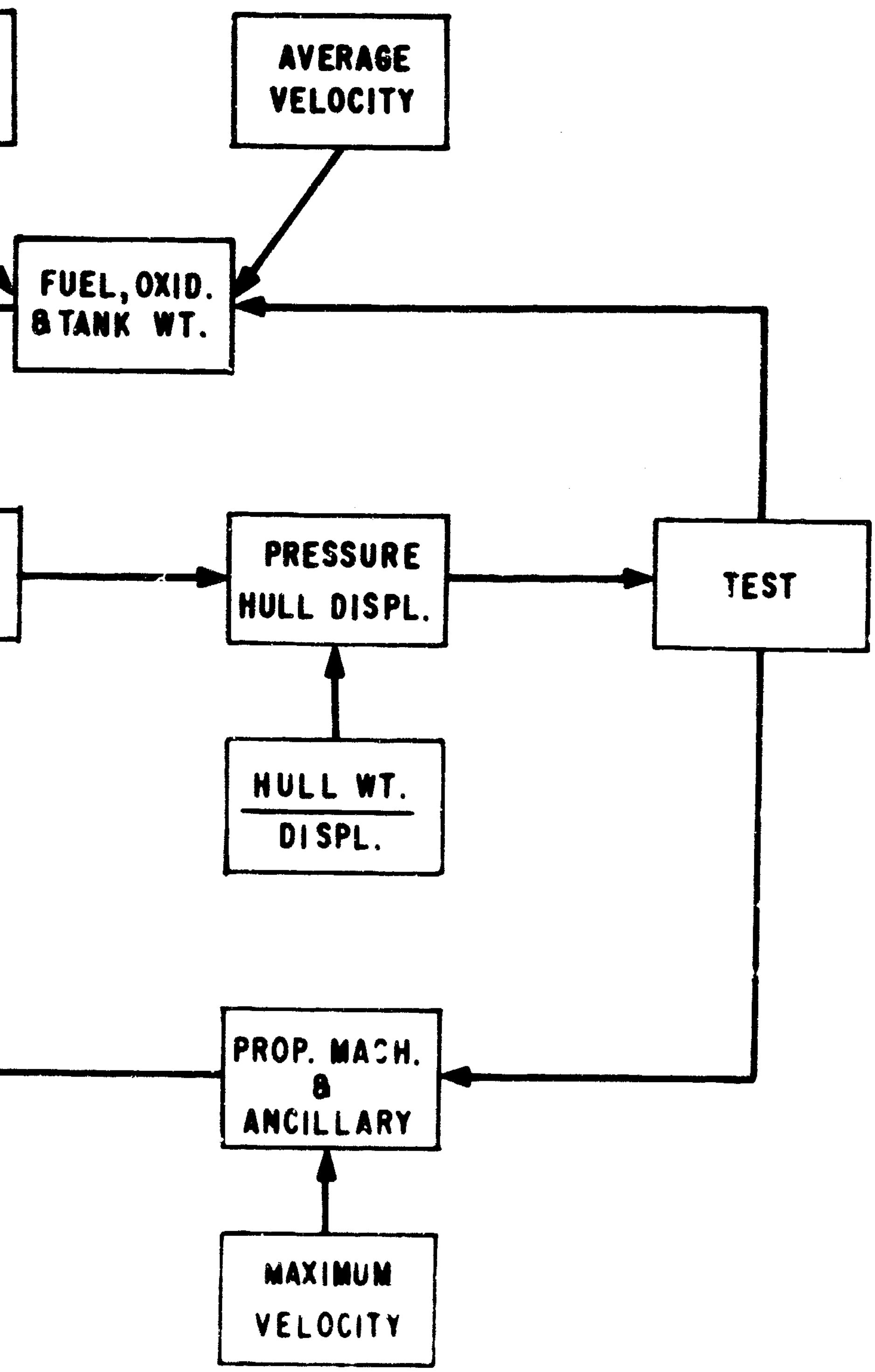
Before a detailed development of the program is presented, it may be well to explain the basic assumptions which have been used in formulating the program. Figure 4(a) shows that all of the ship components, except the main ballast, have been fitted into the pressure hull.

Simplified Flow Diagram Syn



FIGURE

SYNTHESIS OF APPLIED PROPULSION SYSTEMS



ARRANGEMENT OF PRINCIPLE SHIP COMPONENTS

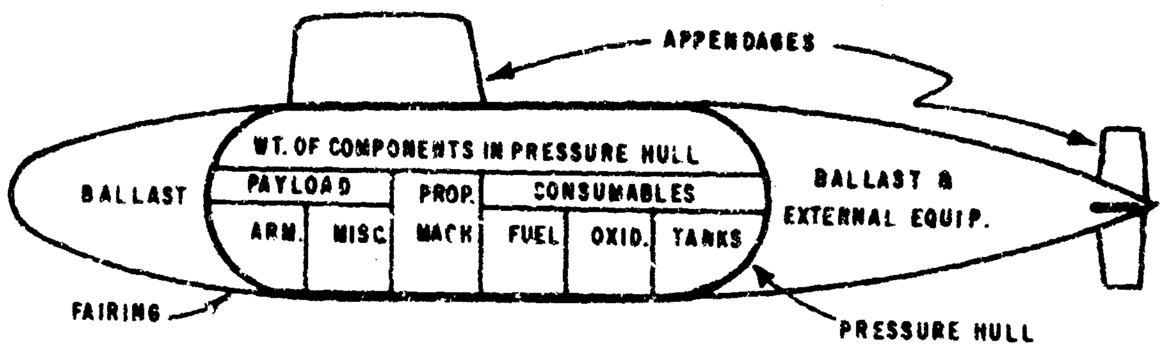


FIGURE 4(A)

PRESSURE HULL FRACTION AS A FUNCTION OF SUBMERGENCE DEPTH AND MATERIAL STRENGTH

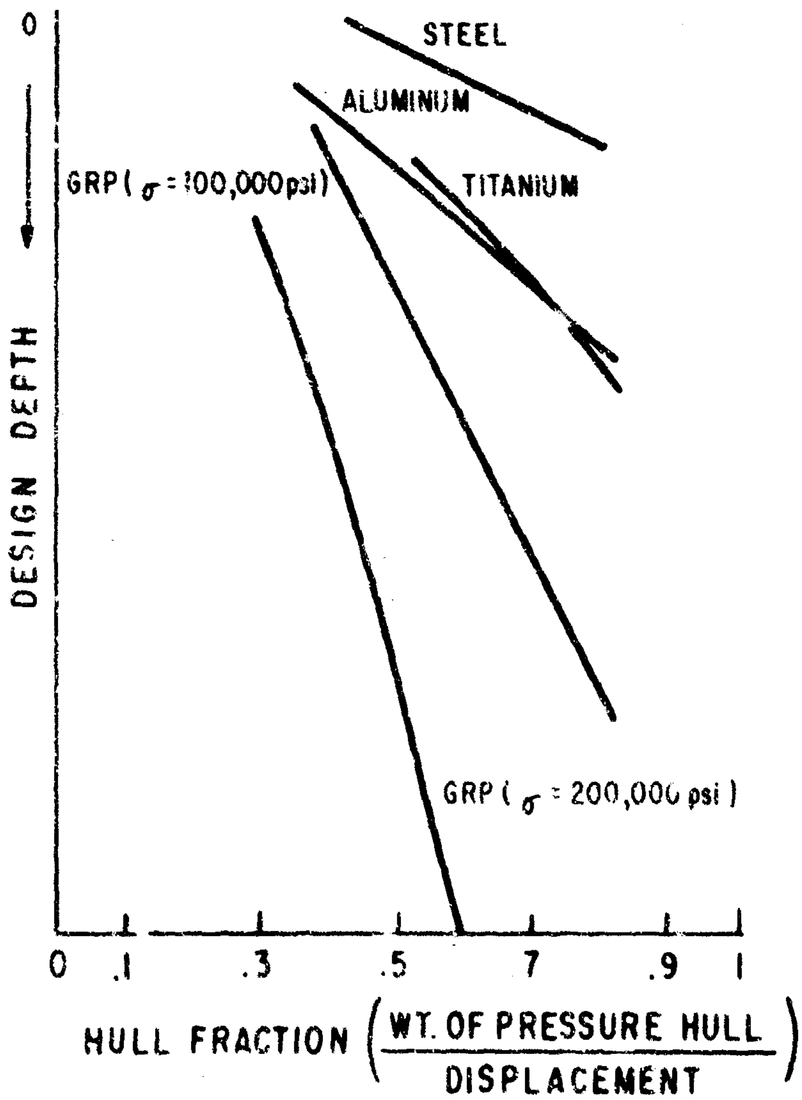


FIGURE 4(B)

THESE INCLUDE PAYLOAD, PROPULSION MACHINERY, AND PROPULSION SYSTEM CONSUMABLES. PAYLOAD IS A CATCH-ALL QUANTITY, WHICH INCLUDES ARMAMENT AND MISCELLANEOUS ITEMS, SUCH AS ELECTRIC PLANT, COMMUNICATIONS AND CONTROL, AUXILIARY SYSTEMS, OUTFIT AND FURNISHINGS, EFFECTIVE FAIRING WEIGHT, AND CONSUMABLES FOR AUXILIARY POWER.

THE VEHICLE IS FAIRED TO PROVIDE A NEAR-OPTIMUM HYDRODYNAMIC SHAPE SIMILAR TO THAT OF ALBACORE. THE PRESSURE-HULL WEIGHT IS DETERMINED FROM DATMOBAS DATA REPRESENTING HULL FRACTION AS A FUNCTION OF SUBMERGENCE DEPTH AND HULL-MATERIAL STRENGTH, AS SHOWN IN FIGURE 4(B). HULL FRACTION IS THE RATIO OF THE PRESSURE HULL WEIGHT TO THE WEIGHT OF ITS DISPLACEMENT.

A SUMMARY OF THE PROGRAM INPUT DESIGN CRITERIA AND OUTPUT PARAMETERS IS SHOWN IN TABLE 2. ALSO PROVIDED IN TABLE 2 IS THE NOMENCLATURE PERTAINING TO THE FOLLOWING ANALYSIS:

REFERRING TO FIGURE 5, THE PROGRAM STARTS WITH THE CALCULATION OF PAYLOAD,

1. $WP \quad WA + WS$

2. $WT = WP + WM + WPR$

   WHERE WT = TOTAL WEIGHT OF ALL SYSTEMS IN THE PRESSURE HULL.

3. $D_T = WT/(1 - DK)$

   WHERE D_T = DISPLACEMENT OF THE PRESSURE HULL FOR NEUTRAL BUOYANCY.

4. $DT = D_T \times RBF$

5. $V_{SUB} = DT/RHO$

   WHERE V_{SUB} = SUBMERGED VOLUME OF THE TOTAL VEHICLE.

6. $D = \sqrt[3]{\dfrac{4\ V_{SUB}}{CP\ \pi\ (DL)}}$

TABLE 2

INPUT AND OUTPUT DATA

INPUT DATA

AA	=	APPENDAGE ALLOWANCE
C	=	CONVERGENCE CRITERIA
CP	=	PRISMATIC COEFFICIENT
CS	=	WETTED-SURFACE COEFFICIENT
DEPTH	=	DEPTH OF SUBMERGENCE IN FEET
DK	=	HULL FRACTION, HULL WEIGHT/DISPLACEMENT, KD
DL	=	L/D; LENGTH/MAXIMUM DIAMETER
FUEL	=	FUEL WEIGHT/BRAKE HORSEPOWER HOUR IN $\frac{LB}{BHP\text{-}HR}$
N	=	NUMBER OF ITERATIONS
OXID	=	OXIDANT WEIGHT/BRAKE HORSEPOWER HOUR IN $\frac{LB}{BHP\text{-}HR}$
PN	=	N_P; PROPULSION EFFICIENCY
RBF	=	RESERVE BUOYANCY FACTOR
RHO	=	RHO OF SEA WATER IN $\frac{LB}{CU\ FT}$
S	=	CRUISE RADIUS IN NAUTICAL MILES
TFF	=	TANKAGE FACTOR OF FUEL; TANK WEIGHT/FUEL WEIGHT
TFO	=	TANKAGE FACTOR OF OXIDANT; TANK WEIGHT/OXIDANT WEIGHT
V(2)	=	AVERAGE VELOCITY, I.E., CRUISING SPEED IN KNOTS
V(1)	=	MAXIMUM VELOCITY IN KNOTS
WA	=	WEIGHT OF ARMAMENTS IN POUNDS
WS	=	WEIGHT OF SYSTEMS IN POUNDS (ELECTRIC PLANT; COMMUNICATION AND CONTROL; AUXILIARY SYSTEMS; AND OUTFIT AND FURNISHINGS)
FN	=	FUEL EFFICIENCY RATIO[1]
CCF	=	CONSUMABLE CORRECTION FACTOR (FUEL EXTERNAL TO HULL)
F	=	F(M) SPECIFIC MACHINERY WEIGHT IN LB/SHP(1)
TN	=	TRANSMISSION EFFICIENCY

OUTPUT DATA

DT	=	TOTAL SUBMERGED DISPLACEMENT
L	=	LENGTH
D	=	MAXIMUM DIAMETER
A	=	BARE HULL WETTED AREA
SHP(1)	=	MAXIMUM PROPULSION POWER
WM	=	PROPULSION MACHINERY AND ANCILLARY WEIGHT
WF	=	WEIGHT OF FUEL
WO	=	WEIGHT OF OXIDANT
WST	=	WEIGHT OF STORAGE TANKS
WPR	=	TOTAL WEIGHT OF FUEL, OXIDANT, AND TANKS
WP	=	PAYLOAD
BHP(2)	=	NORMAL CRUISE POWER
WMPR	=	WM + WPR
HW	=	HULL WEIGHT
BW	=	BALLAST WEIGHT

[1] FUEL EFFICIENCY RATIO IS A RATIO OF THERMAL EFFICIENCY AT REDUCED LOAD TO THE EFFICIENCY AT RATED LOAD.

COMPLETE FLOW DIAGRAM SYNTHESIS OF APPLIE

NOTE:
REFER TO TABLE II
FOR NOMENCLATURE

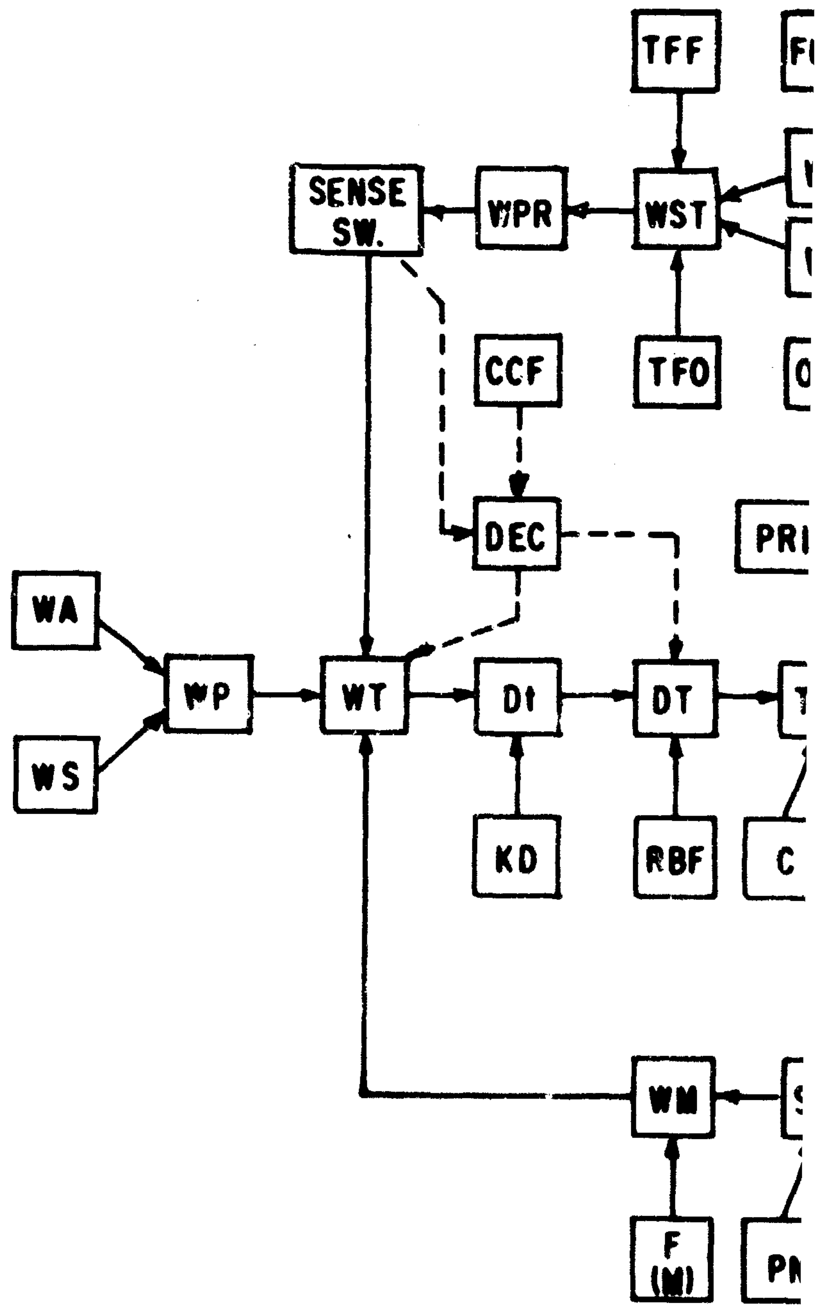
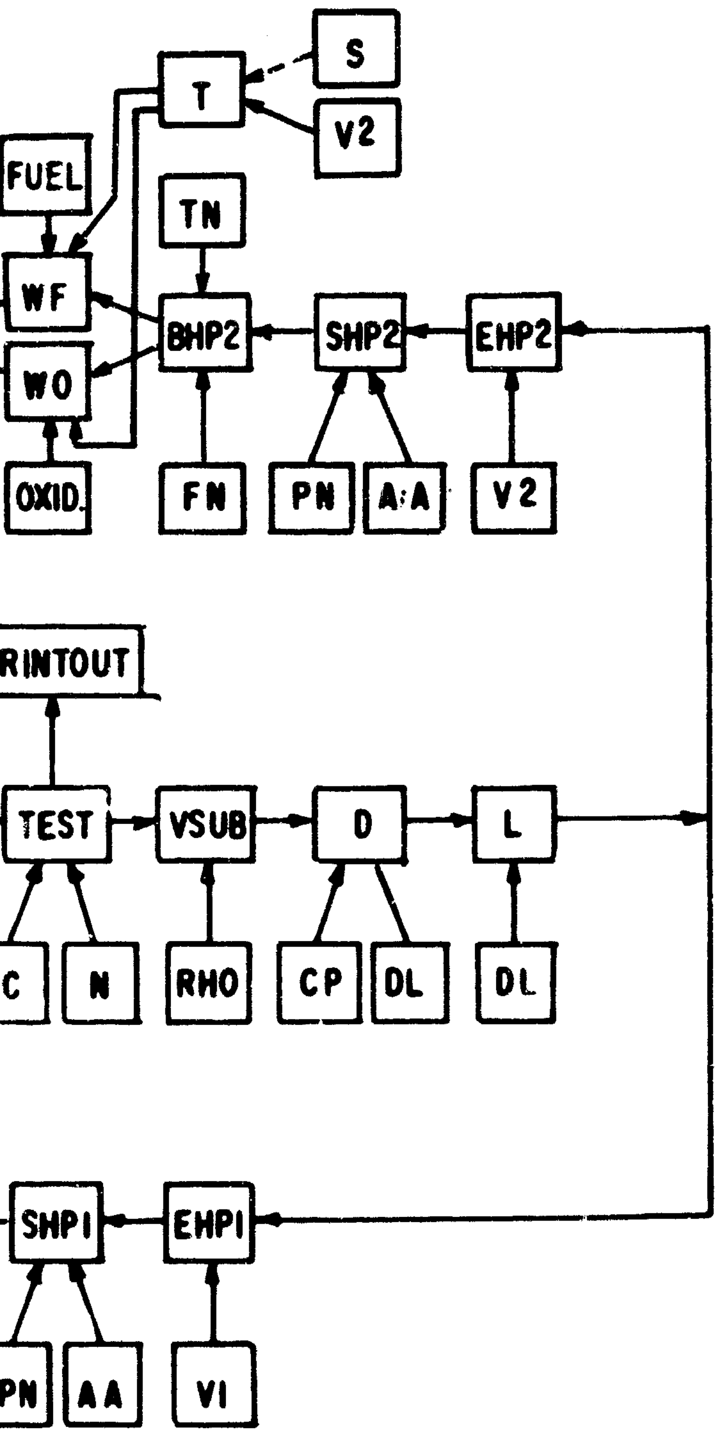


FIGURE 5

ɪED Propulsion Systems



7. $L = (DL)\,D$ $\qquad A = CS\,\pi\,(D)\,L$

8. EHP(1) = (SEE REFERENCES (12) AND (13).)

WHERE EHP(1) = EFFECTIVE HORSEPOWER AT MAXIMUM SHIP VELOCITY.

9. $SHP(1) = \frac{AA}{PN}\,(EHP(1))$

10. $WM = SHP(1) \times F$

11. EHP(2) = (SEE REFERENCES (12) AND (13).)

WHERE EHP(2) = EFFECTIVE HORSEPOWER AT THE NORMAL CRUISE VELOCITY.

12. $SHP(2) = \frac{AA}{PN}\,EHP(2)$

13. $BHP(2) = \frac{SHP(2)}{TN \times FN}$

WHERE TN = TRANSMISSION EFFICIENCY.

FN = FUEL EFFICIENCY RATIO.

BHP(2) = BRAKE HORSEPOWER AT NORMAL CRUISE VELOCITY.

14. $T = \frac{S}{V(2)}$

WHERE T = CRUISE TIME.

15. $WF = BHP(2) \times T \times FUEL$

16. $WO = BHP(2) \times T \times OXID$

17. $WST = WF \times TFF + WO \times TFO$

18. $WPR = WF + WO + WST$

19. $HW = \frac{DT}{RBF}\,(DK)$

20. $BW = DT\,\left(1 - \frac{1}{RBF}\right)$

CONSIDERING THE FUEL AND OXIDANT TO BE STORED IN THE PRESSURE HULL, THE PROGRAM REITERATES:

$$WT = WP + WM * WPR$$

$DT = ETC$ (NEXT ITERATION)

GO TO TEST

TEST: $\frac{DT_2 - DT_1}{DT_2}$ <C GO TO PRINT OUT; >C FIND NEW DT

WITH FUEL AND OXIDANT STORED EXTERNAL TO THE PRESSURE HULL,

$$WT = WP + WM + (WPR(1 - CCF))$$

$$DT(3) = \frac{WT}{1 - DK}$$

WHERE $DT(3)$ = DISPLACEMENT OF PRESSURE HULL.

$$DPR = WPR \times CCF$$

$$DT = (DT(3) + DPR)\ RBF$$

$$HW = DT(3)\ (DK)$$

Exploration of Parameters

AN EXPLORATORY STUDY USING THE FORTRAN PROGRAM (SOAPS) TO SYNTHESIZE APPLIED PROPULSION SYSTEMS HAS BEEN CONDUCTED. THIS STUDY WAS PERFORMED TO OBTAIN PRELIMINARY GUIDANCE CONCERNING THE FOLLOWING QUESTIONS:

A. WHAT DESIGN PARAMETERS HAVE THE MOST SIGNIFICANT EFFECT ON A SHIP?

B. WHAT TYPE OF DATA ON PROPULSION SYSTEMS IS MOST REQUIRED?

C. WHAT ITEMS OF A PROPULSION PLANT SHOULD BE GIVEN MOST EMPHASIS?

D. WHAT CRUISE VELOCITY AND RANGES ARE PRACTICAL FOR PROJECTED PROPULSION PLANTS?

E. WHAT ARE TYPICAL SHIP DISPLACEMENTS FOR A VARIETY OF MISSIONS?

F. WHAT IS ADDED TO SUBMERGED DISPLACEMENT WHEN A POUND OF PAYLOAD IS ADDED TO THE SHIP?

TO ANSWER THESE QUESTIONS AND MANY MORE, THE DATA AS SHOWN IN TABLE 3, REPRESENTING 243 DISCRETE SHIP DESIGNS, HAVE BEEN PROCESSED.

ALTHOUGH SOME OF THE RESULTS WHICH WILL BE PRESENTED IN THE FOLLOWING SECTIONS OF THE PAPER ARE WELL UNDERSTOOD BY THE PEOPLE WHO DESIGN AND BUILD SUBMARINES, THESE PRESENTATIONS WILL SHOW HOW THE PROGRAM MAY HANDLE THE UNSPECIFIED AND UNIQUE CONSIDERATION WHEN FACTUAL DATA REPRESENTING THE ANTICIPATED SYSTEMS BECOME AVAILABLE.

FIGURE 6 SHOWS THE STRONG EFFECT OF SPECIFIC FUEL CONSUMPTION ON SUBMERGED DISPLACEMENT AS A FUNCTION OF VELOCITY AND CRUISE RANGE. IT IS CONSIDERED IMPORTANT TO NOTE THAT, FOR THE LOW-VELOCITY, SHORT-RANGE MISSIONS, THE SPECIFIC FUEL CONSUMPTION DOES NOT SIGNIFICANTLY INFLUENCE SUBMERGED DISPLACEMENT. FOR THE HIGH-VELOCITY, LONG-RANGE MISSIONS, SUBMERGED DISPLACEMENT IS APPROXIMATELY A DIRECT FUNCTION OF SPECIFIC FUEL CONSUMPTION. THE OVERTAKING CHARACTERISTIC OF CONSUMABLES ON THE PAYLOAD FRACTION (PAYLOAD HELD CONSTANT) AS RANGE AND VELOCITY ARE INCREASED IS ALSO SHOWN IN FIGURE 6.

TABLE 3

CRITERIA FOR EXPLORATORY STUDY

RANGE:	5,000, 10,000, 15,000 NM
VELOCITY:	5, 10, 15 KNOTS (V MAX = V AVG)
PAYLOAD:	(0.1, 1.0, 3.0) 10^6 LB
HULL FORM:	(SOLID OF REVOLUTION ((DL = 7.0
APPENDAGE ALLOWANCE:	1.15
RBF:	1.1
SPECIFIC MACHINE WEIGHT:	10 40 70 LB/EHP
SPECIFIC CONSUMABLES:	1, 2, 3 LB/EHP-HR

EFFECT OF SPECIFIC FUEL CONSUMPTION

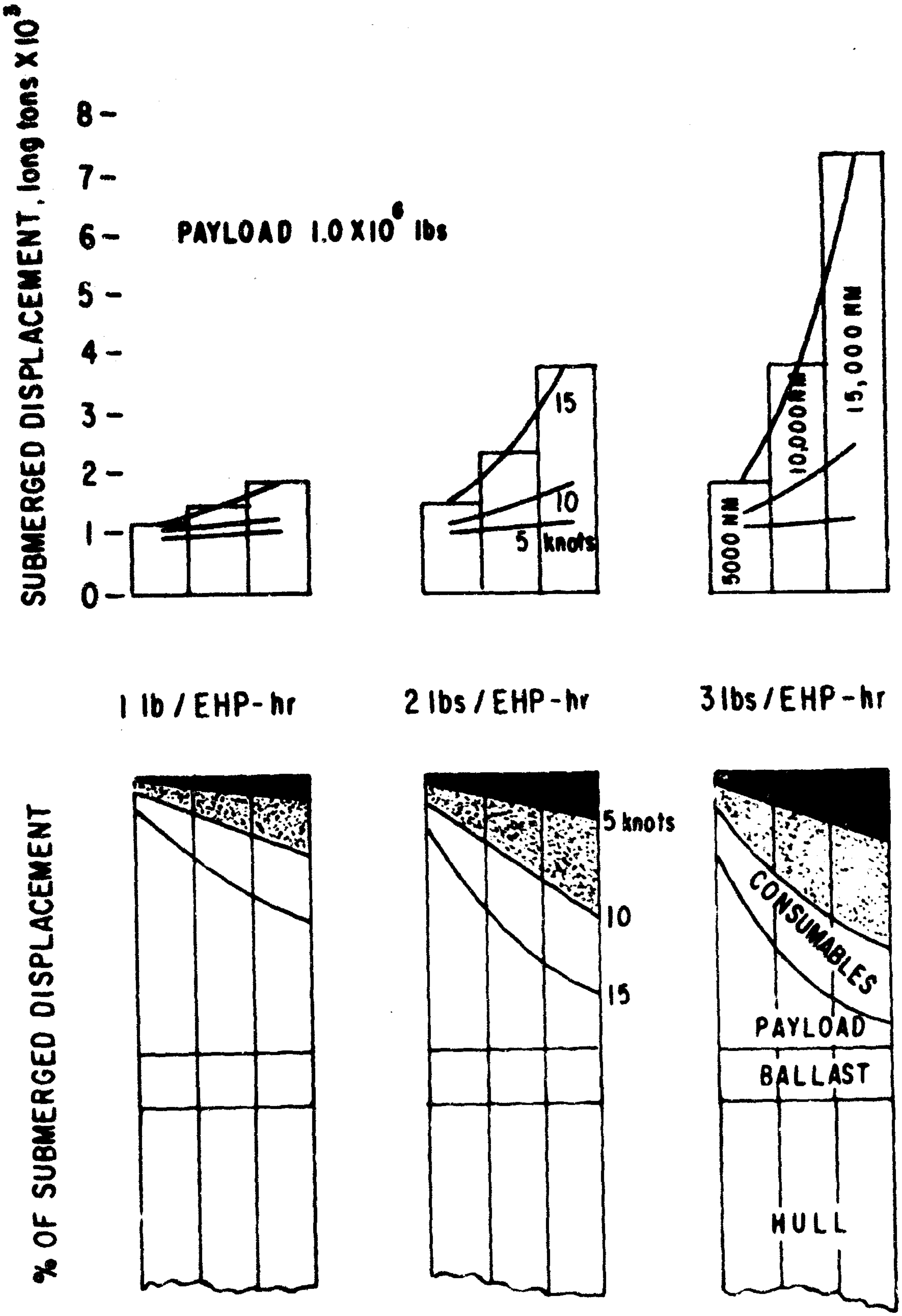
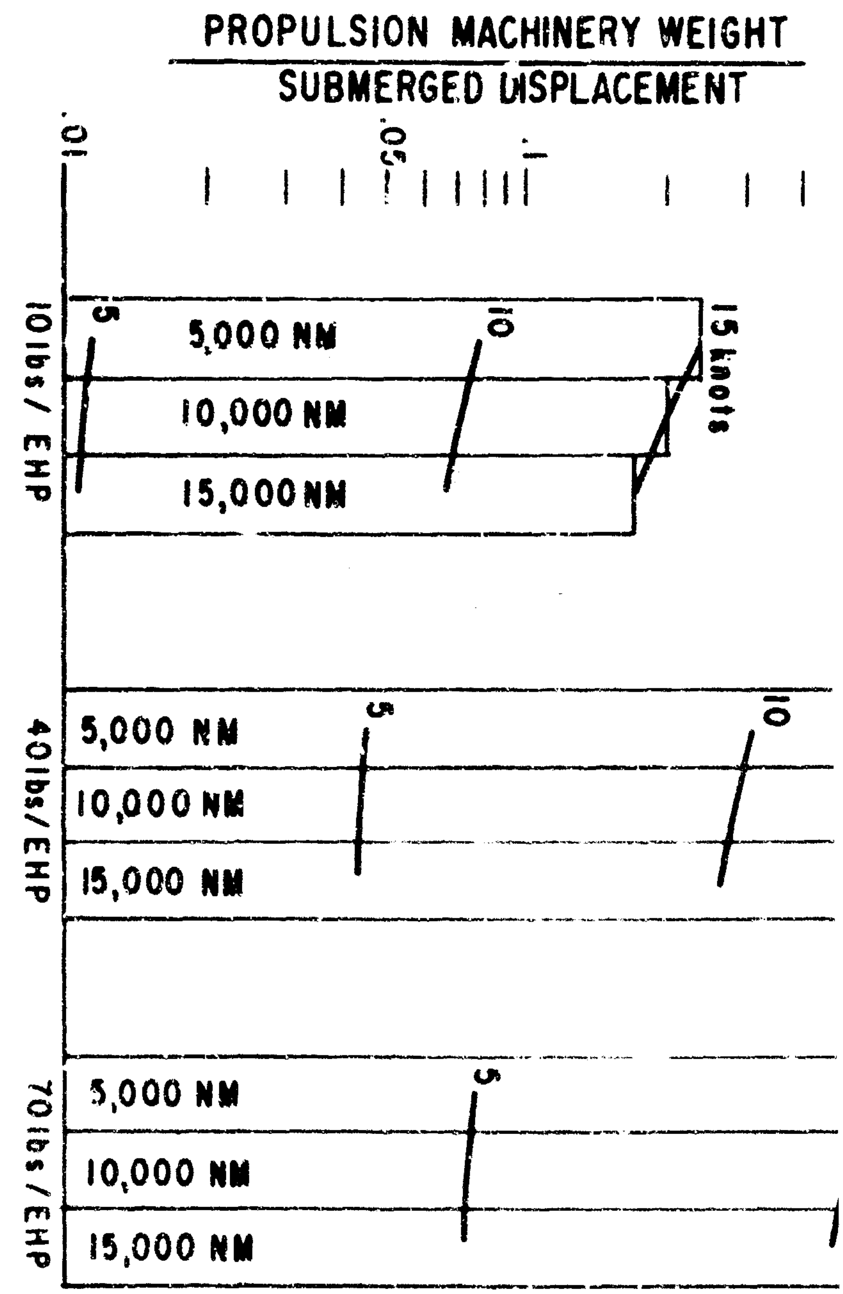


Figure 7 shows the effect of specific propulsion machinery weight on submerged displacement. It is noted that an increase in specific machinery weight from 10 to 40 and then to 70 pounds/EHP increases the fraction of machinery weight to submerged displacement from 0.2 to 1.5% for the synthesized mission and vehicle parameters. The payload, consumables, ballast, and hull structure represent more than 98% of the total submerged displacement.

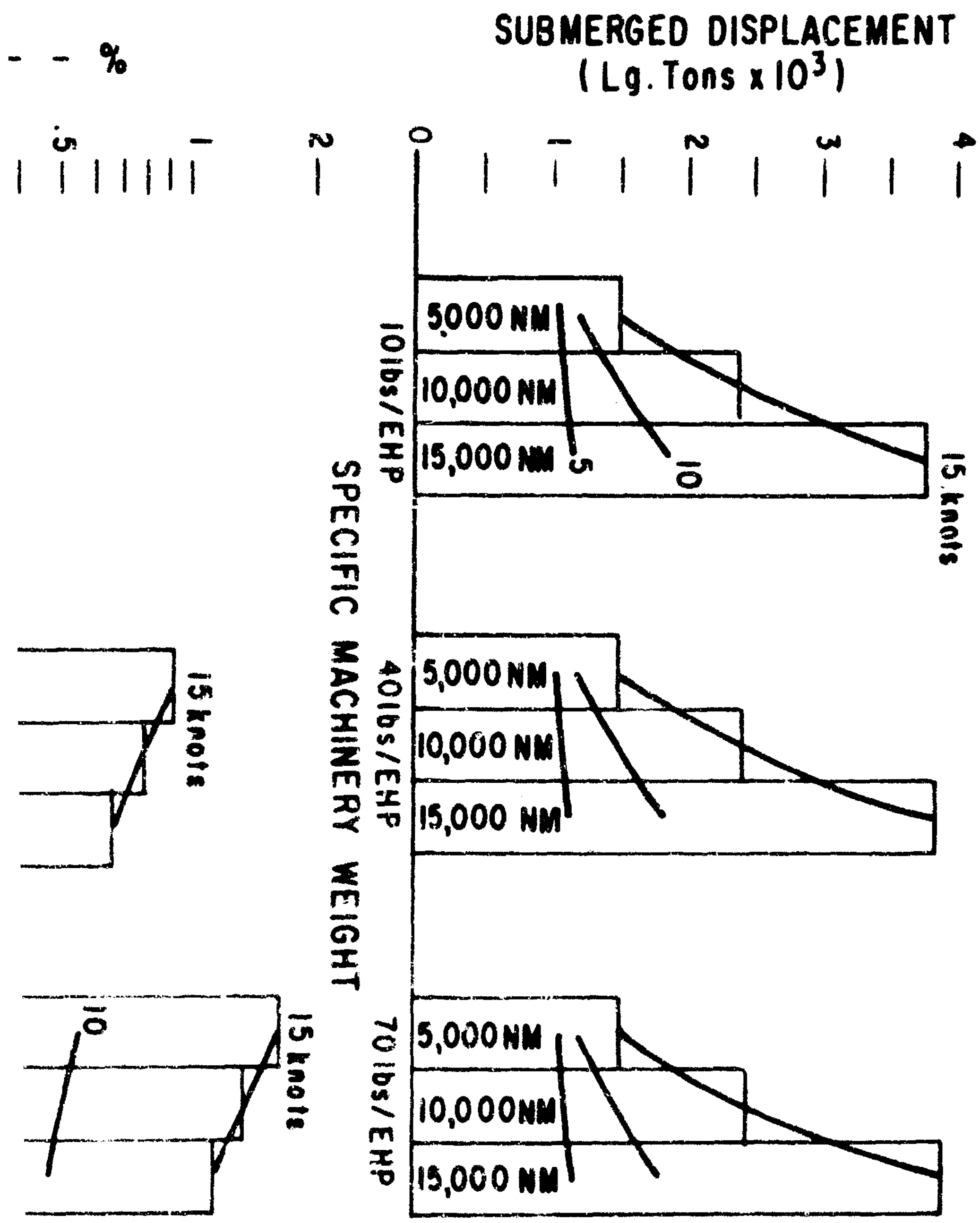
In the course of our studies, it has often been questioned "What is the savings in displacement when an item of machinery is located external to the pressure hull as compared to an internal location?" Figure 8 shows that with a large hull fraction (KD) and a component with a low mean density, a significant reduction in displacement per unit of component weight can be realized by external location. However, the lower the hull fraction and the greater the mean density of the component, the less reduction is noted.

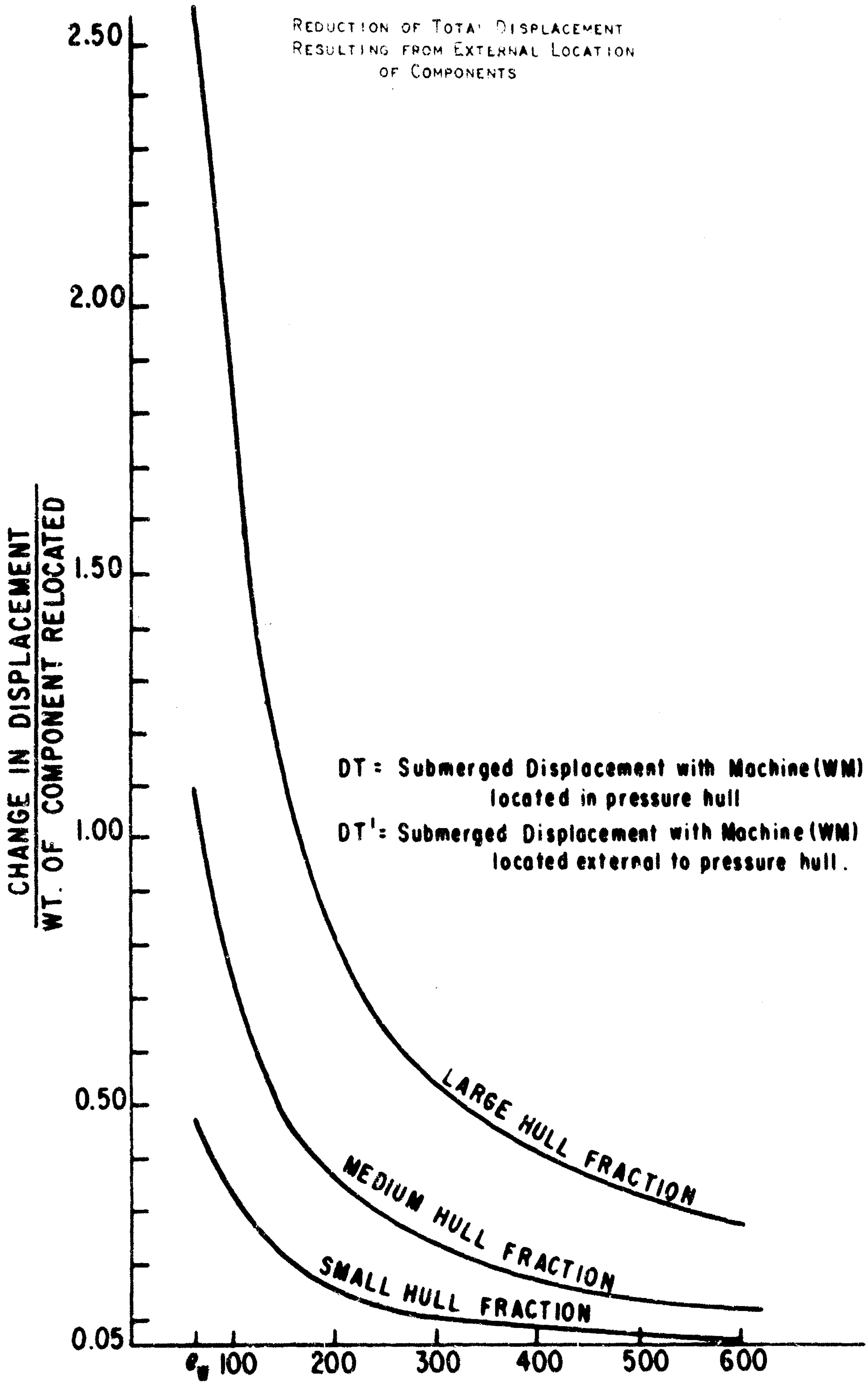
Consider a 1000-pound machinery component having a mean density of 300 pounds/cubic foot, located external to a pressure hull of medium hull fraction. The combined displacement of the pressure hull and machinery components would be reduced by 250 pounds, as compared to the internal location of the same component.

For the mission specified in Figure 9, it is shown that hull weight and total submerged displacement are a function of consumables location, consumption rate, and mean density.

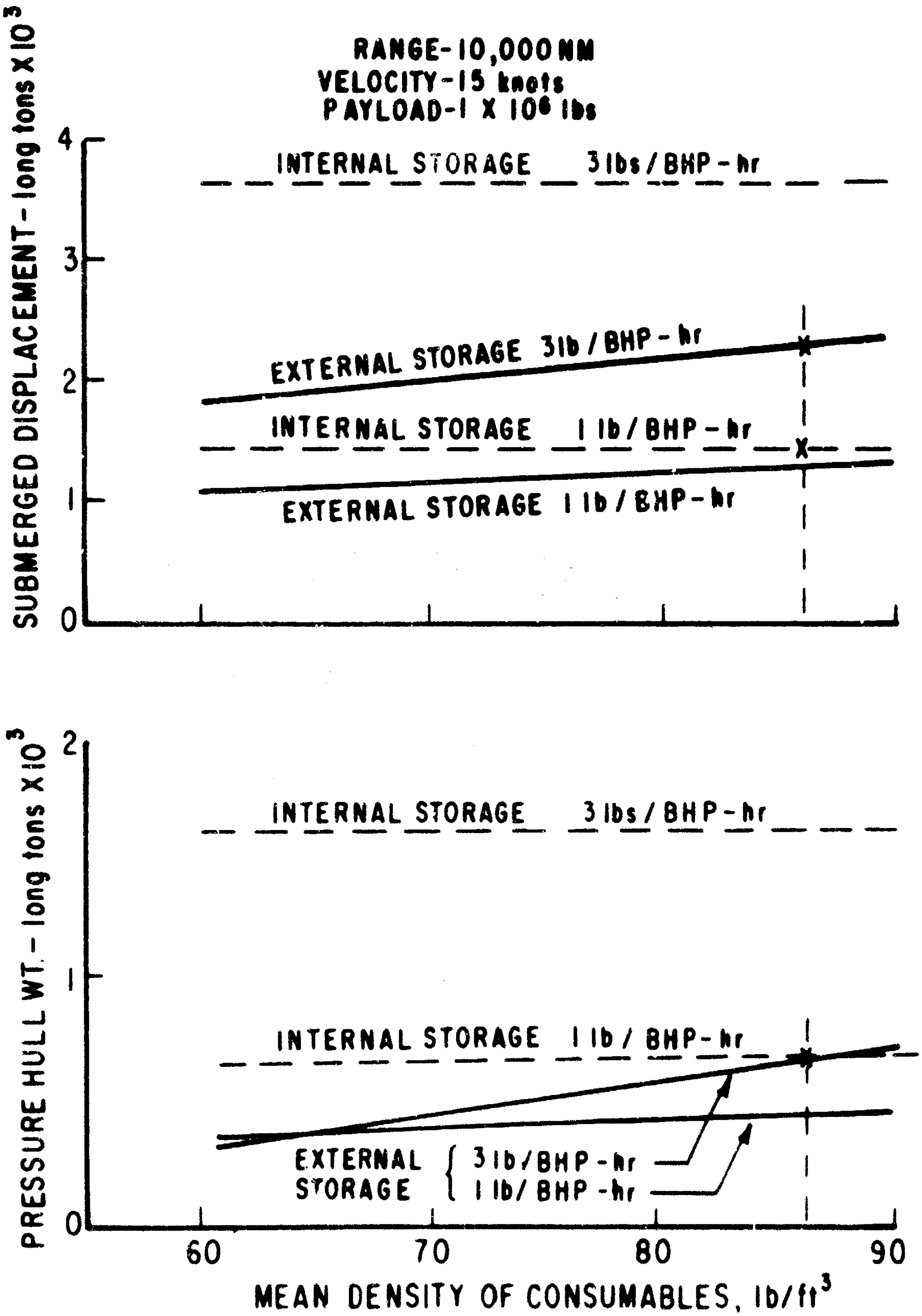

PROPULSION MACHINERY WEIGHT
SUBMERGED DISPLACEMENT
.01
.05
.1
10 lbs / EHP
5,000 NM
10,000 NM
15,000 NM
5
10
15 knots
40 lbs/EHP
5,000 NM
10,000 NM
15,000 NM
5
10
70 lbs/EHP
5,000 NM
10,000 NM
15,000 NM
5

NERY WEIGHT ON SUBMERGED DISPLACEMENT





REDUCTION OF TOTAL DISPLACEMENT RESULTING FROM EXTERNAL LOCATION OF COMPONENTS



... Storage of Consumables Vs External Storage

FIGURE

The results shown in Figure 9 indicate that consumables with a low energy density (3 pounds/EHP-hour), which are capable of being stored external to the pressure hull, can be carried by a ship having a small pressure hull or a pressure hull equal in size to that of a ship using high energy density consumable (1 pound/EHP-hour) carried within the pressure hull. For an example, a ship using 3 pounds/EHP-hour consumables with a mean density of 86 pounds/cubic foot and located external to the pressure hull would require the same size pressure hull (for neutral buoyancy) as a ship using high energy consumables (1 pound/EHP-hour) which are carried within the pressure hull. It is important to note that, although the ship would have a relatively small pressure hull as provided in the above example, the total submerged displacement would be larger in the case where the low energy density consumables are employed.

Figure 10 shows the ratio of displacement to payload for the synthesized vessels. It is shown that higher velocity and longer cruising ranges imply values of 3 to 5 pounds for reasonable payloads of 1×10^6 to 3×10^6 pounds. Small payloads in the order of 100,000 pounds present a substantially higher displacement to payload ratio.

Figure 11 indicates the method by which submarines of specified characteristics can be selected for an optimum payload, speed, and range combination. This approach was presented in a paper which outlined feasibility studies for a hydrofoil craft.(14) A ratio of payload to displacement is plotted against cruise velocity.

Displacement/Payload Vs Range, Velocity, and Total Payload

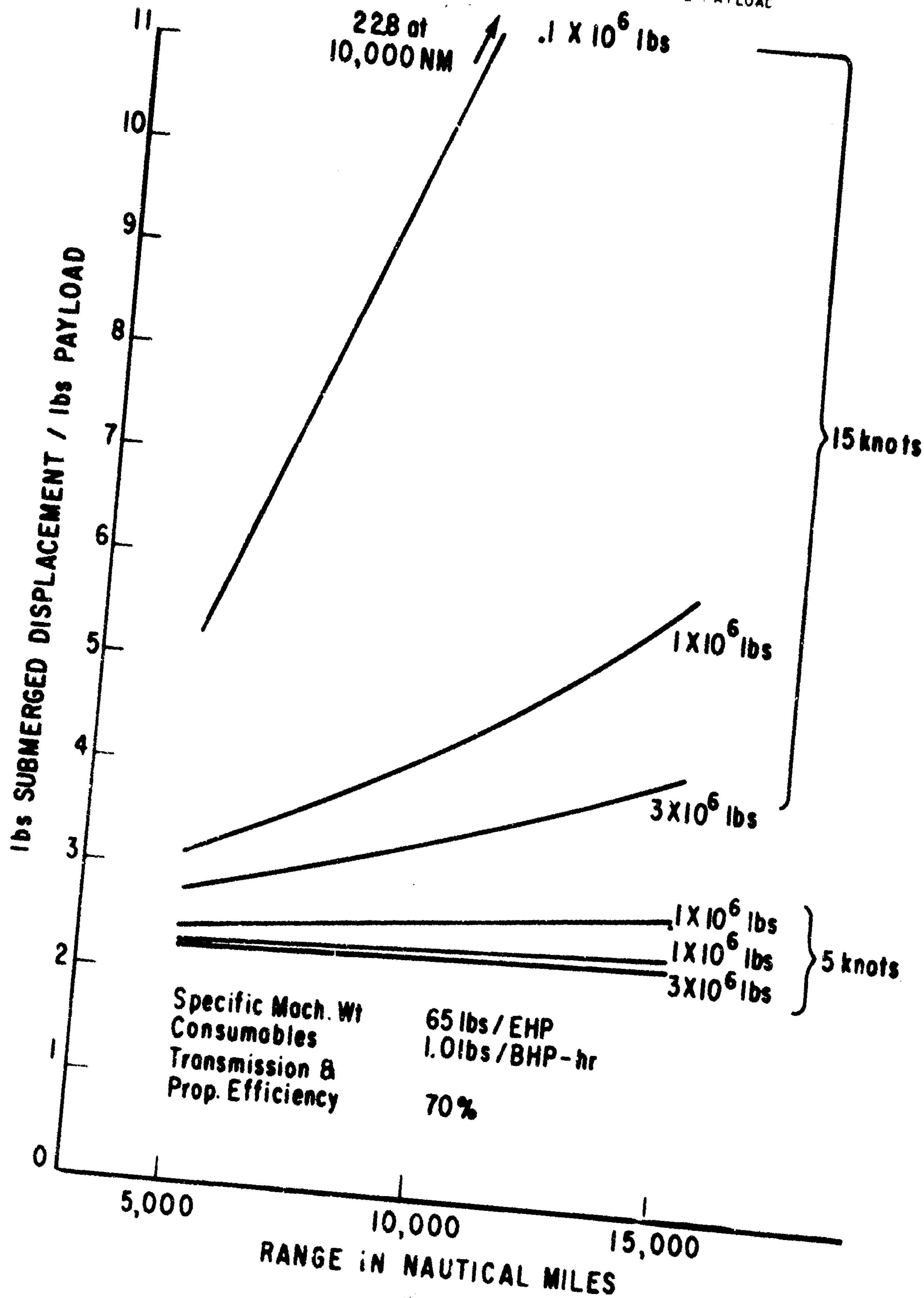
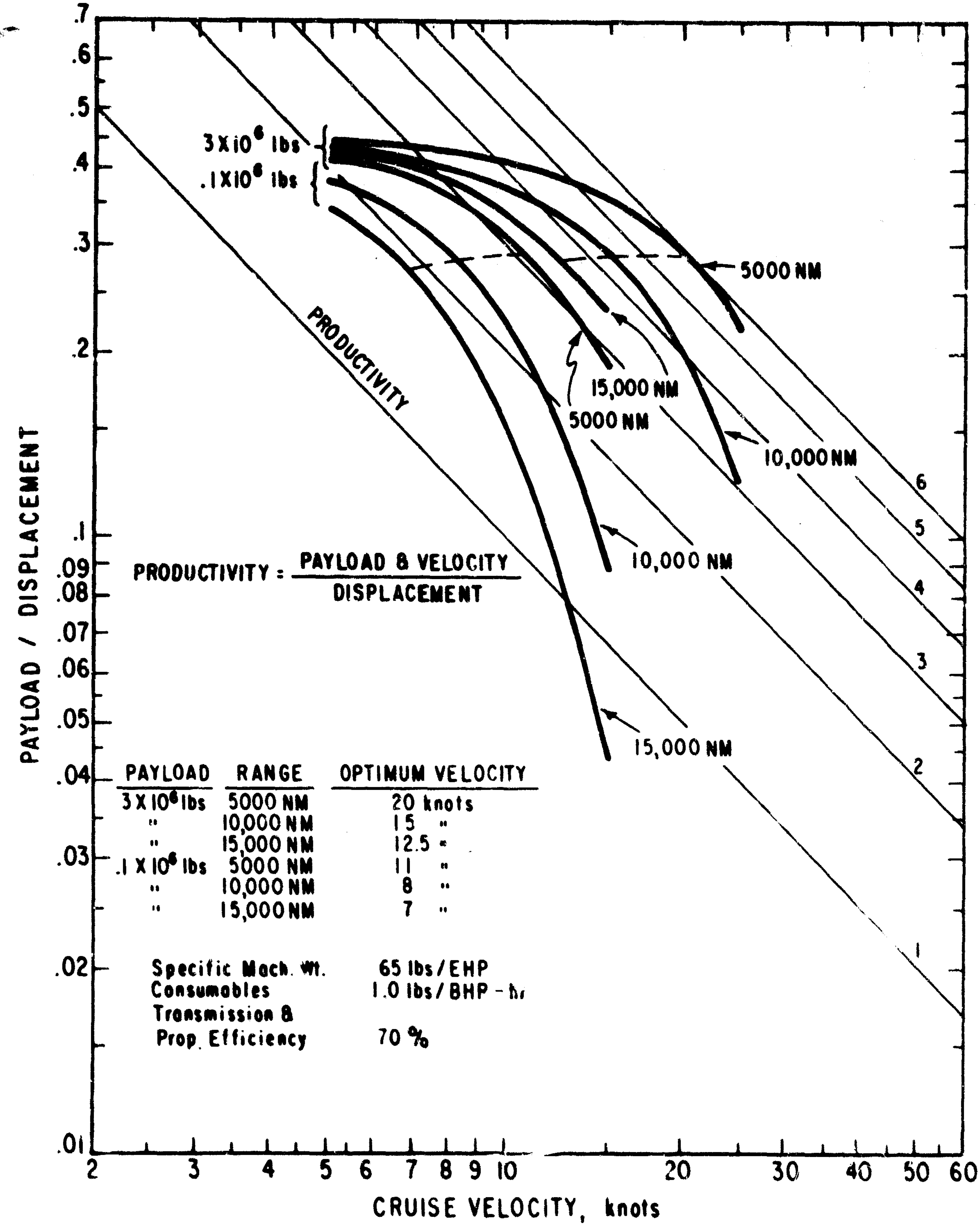


Figure 10


PAYLOAD / DISPLACEMENT
CRUISE VELOCITY, knots
3 X 10^6 lbs
.1 X 10^6 lbs
PRODUCTIVITY
5000 NM
15,000 NM
5000 NM
10,000 NM
10,000 NM
15,000 NM
1
2
3
4
5
6
PRODUCTIVITY = PAYLOAD & VELOCITY / DISPLACEMENT
PAYLOAD | RANGE | OPTIMUM VELOCITY
3 X 10^6 lbs | 5000 NM | 20 knots
" | 10,000 NM | 15 "
" | 15,000 NM | 12.5 "
.1 X 10^6 lbs | 5000 NM | 11 "
" | 10,000 NM | 8 "
" | 15,000 NM | 7 "
Specific Mach. Wt. 65 lbs/EHP
Consumables 1.0 lbs/BHP - hr
Transmission & Prop. Efficiency 70 %

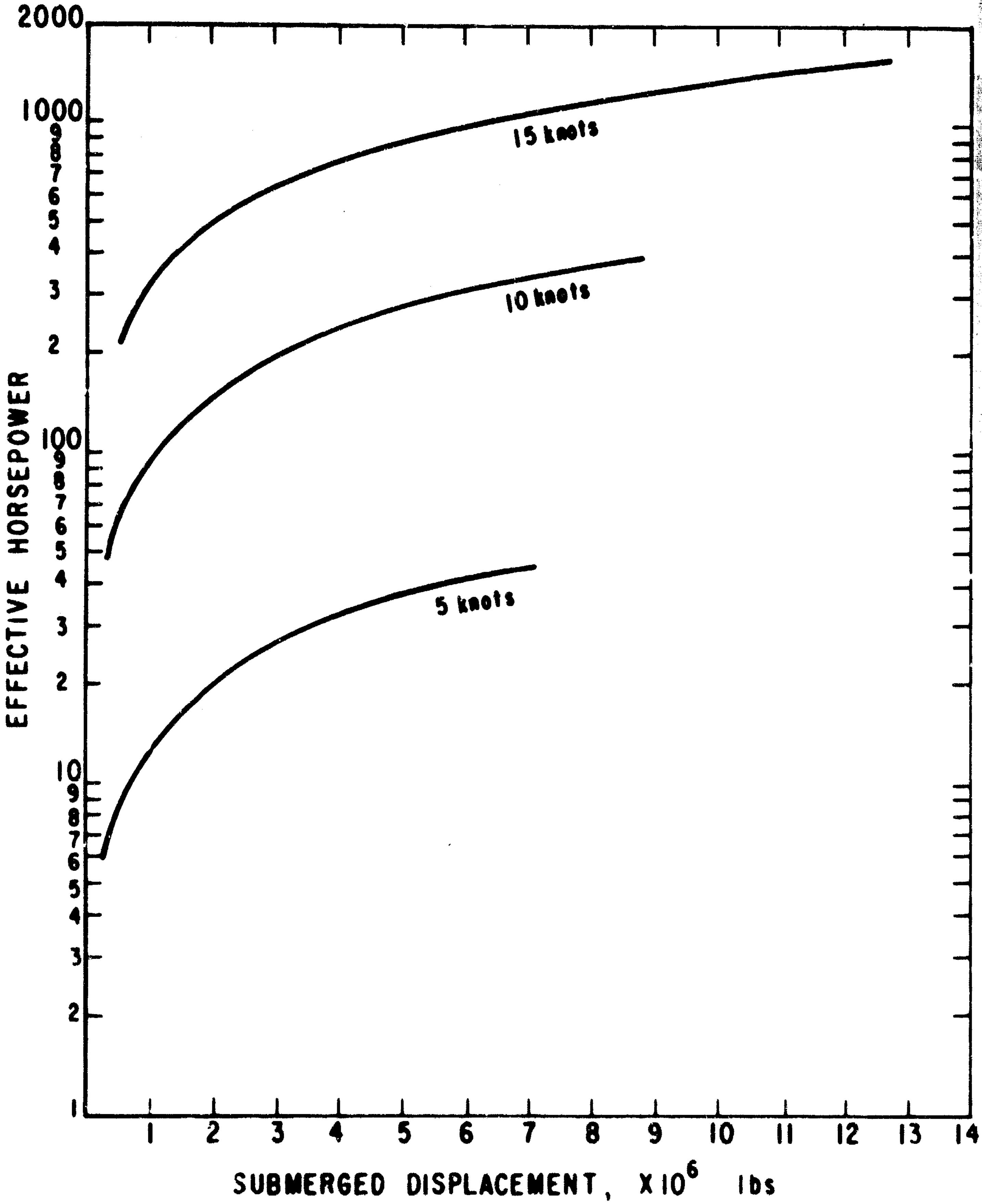
Lines representing a constant "productivity" are drawn diagonally from the ordinate to the abscissa. Productivity is defined as the product of payload and velocity divided by displacement. Cost effectiveness considerations for a weapon carrier generally would point to a maximum productivity, since greater weapon payloads could be transported per unit of displacement. The optimum velocity predicted in Figure 11 is based on the presented hypothetical ship and propulsion plant designs. In general, it is shown that a short cruise range and a large payload correspond with high cruise velocity and high productivity. Relatively small payloads are best transported at a lower velocity.

Figure 12 presents the speed, horsepower, and displacement relationships which were assumed throughout the exploratory studies.

Plant Selection

Figure 13 illustrates a method of presenting a comparison and guide for selecting a minimum weight propulsion plant (including fuel and oxidant) from the many types of anticipated propulsion plants. Effective horsepower is plotted against mission duration. These parameters when combined in this manner present the relation of power rating and energy storage requirements. Boundary lines are drawn to separate the adjacent plant concepts at an interval where the weight of either plant and fuel complement is equal. For a specified effective horsepower requirement and mission duration, an appropriate propulsion plant can be selected.

POWER, SPEED, AND DISPLACEMENT PARAMETERS USED IN EXPLORATORY STUDY



FIGURE

WEIGHT COMPARISON OF PR

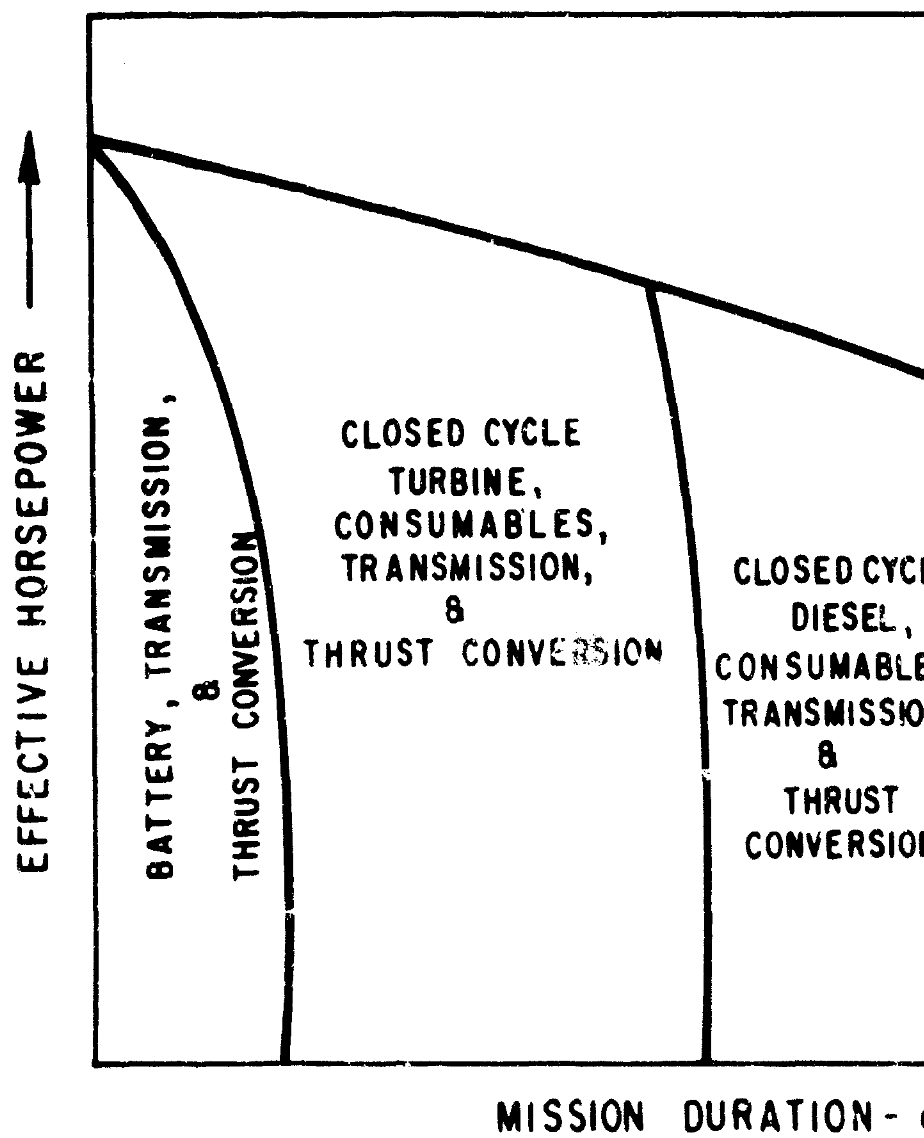
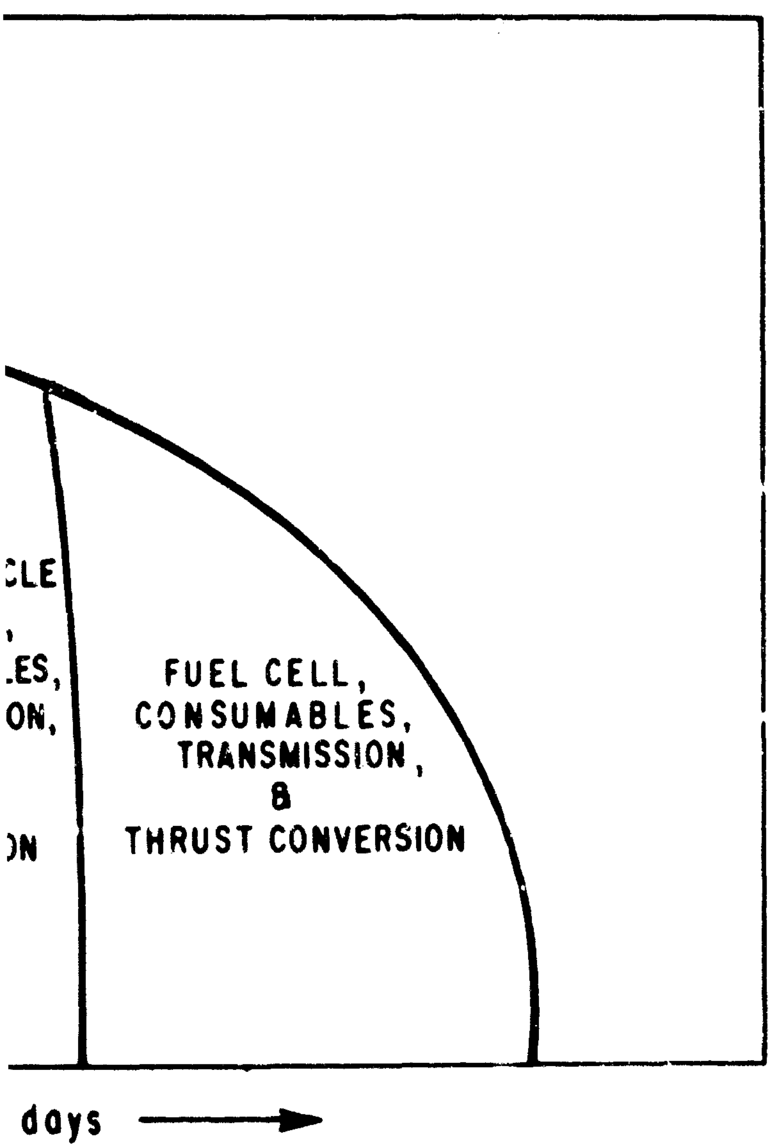


FIGURE 10

PROP SION PLANTS



Since variations in cruise velocity, submergence depth, and cruise endurance significantly modify or rule out candidate systems, it will be necessary to prepare several charts similar to Figure 13 with particular reference to velocity and submergence depth. To prepare these presentations and the corresponding data representing various plant performance and design characteristics, the computer program will be utilized to generate systematic first order data for existing and proposed propulsion plants as they may be applied to submerged vehicles of all descriptions.

The success of our propulsion systems synthesis has provided the impetus to develop additional subroutines to the existing propulsion program representing the ship's auxiliary systems and electrical plant.

Conclusion

Since it is anticipated that eventually deep diving submarines will be weight- rather than volume-limited, a new approach to machinery evaluation and design is required. To realize minimum weight systems, cruising speeds must be conservative. High speeds for long endurance missions would require hull displacements larger than those of presently used submarines. For a specified high energy mission, economy in the use of fuel and oxidant has the most significant effect on ship displacement. Considerable hull weight and therefore displacement can be saved by the external location of power plant consumables and machinery. Considering a typical mission, reductions in rates of fuel and oxidant consumption are more important than reductions in machinery weights.

While the ratio of displacement to payload has been found to be a function of submergence depth, velocity, and range, the magnitude of the payload carried is also quite significant. In general, optimum productivity is represented by large payloads transported at high cruise velocities for short distances. Relatively small payloads are shown to be productively transported at low velocities.

The methods of analysis presented in this paper enable us to review the current status of candidate propulsion systems and their relative abilities to meet the Navy's requirements. The studies indicate areas in which further development promises the most return in improved effectiveness.

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